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Original Article

RESEARCH OF CUTTING TEMPERATURE REDUCING OF TITANIUM ALLOY GRADE 5 BELOW POLYMORPHIC TRANSFORMATION DEPENDING ON CALCULATION OF CUTTING MODES

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ABSTRACT

Titanium alloys not only have high physical and mechanical properties, in addition, they are the most suitable materials for medical use among metal biomaterials. The machinability of titanium alloys depends on the phase and chemical composition, microstructure parameters and selected cutting conditions. Titanium alloy Grade 5 is used for research, its properties are as close as possible to the analogue of medical titanium alloy. Therefore, it is experimentally determined the surface roughness dependence of the implant on the angular velocity of cutting and feeding tool. The results obtained on the optimal processing conditions for the main and auxiliary movements from Grade 5 titanium alloy are similar for a medical alloy and the basis for choosing the exact processing modes in order to ensure the required surface roughness.

The upgraded implant with a double thread provides an increase in translational linear displacement for a full revolution. Rational modes for finishing and double-threading of titanium alloys are defined, and preliminary recommendations on accuracy control for processing difficult titanium implants are proposed. Experimental studies were carried out on a numerically controlled lathe and a vertically milling machine. A technological process has been developed for the manufacture of an implant for the hip tibia using a modified design of double-thread.

KEYWORDS: Implant, Titanium Alloys, Cutting Conditions, Processing Technology, Surface Roughness & Regression Formula

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INTRODUCTION

Materials Used for the Implants Manufacturing

Implants made of metals and their alloys are widely used in traumatology. Recently, titanium-based alloys are actively used in medicine. Internal fixation implants are made of such materials, which should, first of all, meet the tasks of ensuring reliable fracture fixation. This is a rather long period of time; therefore, biocompatible materials resistant to fatigue failure are chosen [1]. They require good ductility for the possibility of individual modeling on the bone surface, at the same time, the plastic deformation of the implant should be minimal at maximum strength after fixation on the surface of bone fragments in order to maintain them in a static position even under physical load [2]. Titanium implants are made for orthopedic dentistry, cardio and facial surgery. In their properties, titanium alloys significantly surpass high-quality types of stainless steel, which eventually damage muscles and bones [3]. VT6 titanium alloy (GOST 19807-91), also known as Grade 5 (US analogue according to ASTM), is a well-machined deformable material. The identified qualities were of interest to physicians after a series of chemical

experiments; metal resistance to hydrogen peroxide, ethyl alcohol, formaldehyde, phenol was noted [4].

Grade 5 titanium alloy includes aluminum, which favorably affects the heat resistance and strength of the implant, as well as vanadium, which can increase the strength of the metal and make it more ductile (Table 1). In addition, oxygen, hydrogen, and nitrogen affect titanium products [5].

Table 1: Chemical Composition of Grade 5 GOST 19807-91 (Grade 5)

Fe	C	Si	V	N	Ti	Al	Zr	O	H	Impurities
to 0,3	to 0,1	to 0,15	**3,5-5,3**	to 0,05	**86,485-91,2**	**5,3-6,8**	to 0,3	to0,2	to 0,015	Other0,3

The material used for implantation must maintain biocompatibility and not change its physical and chemical properties [6]. All metals used in medicine, according to their effects on living tissues, are divided into three main groups: 1) toxic metals (vanadium, nickel, chromium, cobalt); 2) intermediate metals (iron, gold, aluminum); 3) inert metals (titanium, zirconium). Based on the results of the study of electrochemical reactions, M. Pourbaix (1984) concluded that theoretically, noble metals (with a purely metal surface) or five metals are coated with a layer of protective oxides (Ti, Ta, Nb, Zr, Cr). [7].

However, if these metals are introduced into the body, bypassing natural barriers, for example, during their surgical implantation, the content of the above elements in the tissues can increase several times [8]. Therefore, another important requirement for implants is that the metal in direct contact with cells should not damage them or distort the course of biochemical processes in them.

The metallographic analysis showed that the microstructure of the Grade 5 titanium alloy is characterized by the presence of a fine-grained lamellar structure (Figure 1), dispersed particles of the α phase, directly at the boundaries and inside β grains. Fine grain is the result of a small change in volume during β → α - transformation, which causes grain refinement during phase recrystallization, due to the practical absence of phase hardening. It is known that the formation of a lamellar structure in castings of α - and (α + β) - alloys occurs with sufficiently slow cooling during phase recrystallization [9]. The nucleation of α-plates begins at the boundaries of β-grains, and as the cooling cools, the plates grow inside the grain. As a result, bundles of α-plates oriented in the same direction are formed in the grain.

In the traditional machining of titanium alloys without the use of coolant, an increase in temperature occurs in the contact area of the cutter within 1100º-1200ºC (Figure 2). During the heating process, there is a polymorphic transformation of a low-temperature α → β modification of a titanium alloy with a hexagonal close-packed (HCP) lattice into a high-temperature α-modification with a body-centered cubic (BCC) lattice and the reverse transition β → α upon cooling. The temperature of the complete polymorphic transformation α → β → α for pure titanium starts at 822° C, for Grade 5 alloy it depends on the content and type of alloying elements and impurities [10]. In the investigated Grade 5 alloy, the predominantly alloying elements are Al (about 6%) and V (about 4%) also have impurities that affect the polymorphic transformation, and it is in the range of 822^{o}-1020^{o}C. During machining, the temperature rises within 1100º-1200ºC, which is higher than the polymorphic transformation temperature and, as a result, recrystallization practically occurs upon heating, followed by oxidation of the chips.

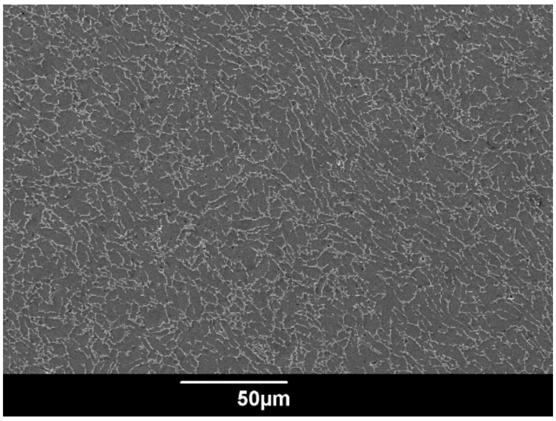


Figure 1: The Initial Microstructure of a Titanium Alloy Grade 5.

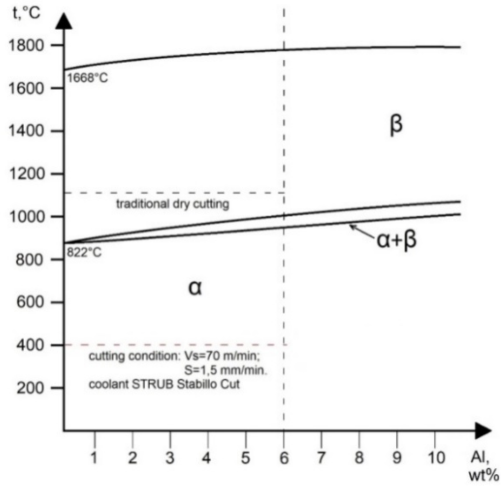


Figure 2: Double diagram of Ti-Al Alloy.

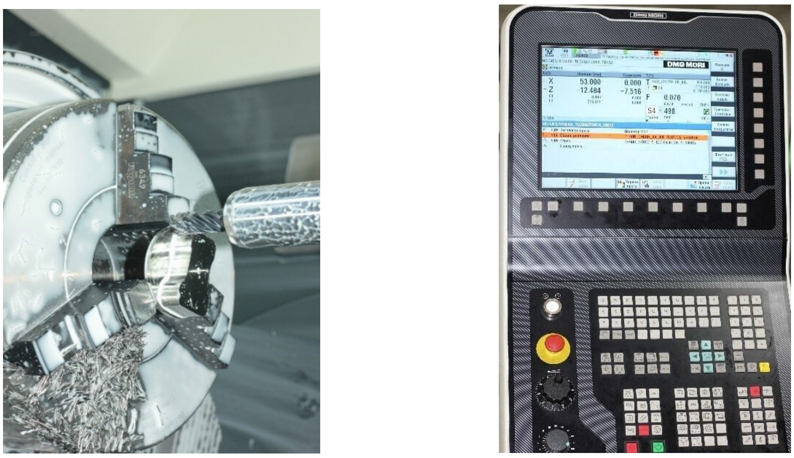
For titanium alloy machining, it is not recommended to exceed the temperature in the cutting area of more than 822 ° C. Application of cutting fluids STRUB Stabilio Cut within the temperature range of 20 ºC does not allow to significantly reduce the processing temperature in the contact area to the required parameters. This leads to the search for methods to reduce temperatures from 1100º-1200ºC, one of which is the determination of optimal modes.

THE TECHNIQUE OF EXPERIMENTS ON THE MECHANICAL PROCESSING OF THE IMPLANT

As part of the implementation of the Target Scientific and Technical Program, D. Serikbaev EKSTU implements the program "Production of titanium products for further use in medicine" to develop a technology for manufacturing medical implants. For the implant manufacturing, a bar made of Grade 5 alloy was selected, which is inserted into the self-centering chuck of a CTX 510 ecoline lathe manufactured by DMGMori [11].

A blank is cut for an implant plate with a spacing diameter of 50 mm and a thickness of 20 mm, for the tibia, with the calculation of machining allowances. The workpiece is installed on a 5-axis vertical milling machine DMU-50 ecolinecnc, Sinumerik 840DC + BacxisTT 5 axi, DMGMori (Figure 3a). CAD modeling was carried out in the SOLIDWORKS 2018 program, CAM programming in Mastercam 2018. Control modules are ERG Olinec CELOS machine, Sinumerki840Dsl, 21.5 MultiTouch touch screen and tactile control panel (Figure 3b). Program control is Simens

Sinumerki 840Dsl machine. The surface roughness was investigated on a non-contact interference 3-D profile graph, with the software "Micron-beta".



(a) (b)

(a) - Rough Milling of the Implant; (b) Control Panel of the Machine Operator

Figure 3: Processing of the Implant on a Vertically Milling Machine DMU - 50 Ecoline

After roughing process in the following modes: main rotation of the end mill - 108 m/min; feed -2.679 mm/min; depth per pass - 1.5 mm, the implant for finishing is obtained. Furthermore, a two-thread is cut in increments of 1 mm, in holes with a diameter of 8 mm. The optimal finishing conditions have been experimentally determined to meet the requirements for accuracy and surface roughness of the implant. After finishing, the implants are anodized and labeled (Figure 4), followed by vacuum packaging.



1-Implant made from Grade 5 after Spraying; 2-Medical Implant Catalog

Figure 4: Tibial Distance Implants.

STUDY RESULTS AND DISCUSSIONS

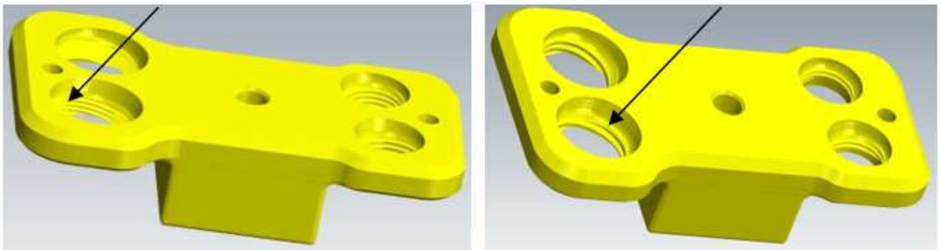
For reliable fixation of the implant to the bone, in addition to the self-tightening thread, a metric thread is used. The thread is designed to maximize initial contact, increase surface area and facilitate stress distribution in the bone-implant contact zone [12]. A single-starting metric thread is cut into the implant of the spacer plate for the tibia from titanium alloy (shown in the figure 5 by the arrow).



Figure 5: Self-Tightening and Metric Threads on the Implant Plate

When designing the implant model, the design was changed and double-thread (Figure 6 b) was modeled instead of a single-thread (Figure 6 a).

It is a well-known fact, that the advantages of double-threading are multiple increase in feed per revolution when tightening, which shortens the fixation time, which is very important in surgical operations [13].



a) b)

Figure 6: Simulation of Implants with One-Way and Two-Way Internal Thread: a) One-Way Thread; b) Two-Way Thread

The geometry of the thread and surface roughness are the main factors in the distribution of load in the area of the implant and the bone being operated on. The implant is finally subjected to electrolysis anodization, this process requires a roughness, at least for finishing. Since this screw is screwed into the bone, excessive manipulations are not desirable [14]. With each turn of twisting into the patient bone, in addition to reducing pain, the operating time is significantly reduced. To satisfy the required parameters for surface roughness, the optimal cutting conditions for double-threading to ensure the reliability of fixation of the implant are experimentally determined. Cutting the internal thread is much more complicated compared to the external thread and requires a special tool [15]. Difficulties are observed when cooling the part, lubricating the teeth of the tap and when removing chips. The metal sticks to the teeth, a buildup forms on the cutting edge and the thread lifts up. As a result, the tap wears out or breaks [16]. For cutting multiple threads, instead of the thread-cutting mill, a special tool manufactured by Kennemetal is used (Figure 7).



Figure 7: Left - Threading Tap for Single-Thread, Right - Special Threading Tool for Two-Thread

For medical metric threads, ISO 68-1-98 (GOST 9150-81) applies, which establishes the nominal profile and dimensions of its elements. According to the standard requirements, landing with a gap is used to provide quick and easy screwed-in metric fastening threads with anticorrosion coatings [17].

To determine the optimal cutting conditions for double-threading, a matrix of experimental design (Table 4) with the main parameters affecting the roughness Ra is developed. With a large roughness of the implant surface, the bone is subjected to unnecessary and excessive transverse shear load [18]. The main parameters affecting the accuracy and surface roughness are: cutting speed V_S, m/min; feed S, mm/min; and the angular velocity per tooth of the cutter V_f, mm/min. For experiments, the cutting conditions were grouped into Range No. 1, Range No. 2 and Range No. 3 (Table 2). The mathematical model allows to quantify the degree of certain factors influence on process indicators, select the most important of them and determine those that can be used in processing [19].

Considering the fact that the angular velocity per cutter tooth V_f is proportional to the angular velocity V_S, the angular velocity per cutter tooth is excluded [20]. Based on the results of the study, a graph of the dependence of surface roughness on the angular cutting speed and linear tool feed is plotted (Figure 8). A direct linear dependence of the roughness on the linear feed, S mm/min, is established. An increase in the angular velocity V_S, m/min, in the first range, leads to an increase in the roughness Ra, the maximum value of which reaches 2.8 µm. A further increase in speed leads to a decrease in roughness in the second and third ranges. The intersection of two curves determines the most optimal processing modes [21].

At a cutting speed of V_S = 70 m/min and a feed rate of S = 1.5 mm/min, which is within the second range, the roughness value is Ra = 1.899 µm, Figure 9. The graph shows the limits of measurement accuracy, which allows to correct for a standard series roughness Ra = 1.6 µm. This value of roughness corresponds to the traditional grinding operation, which satisfies the requirements for implants [22].

Table 2: The Matrix of the Experiments in Various Processing Modes

Range No. 1			Range No. 2			Range No. 3		
$V_f$mm/min	S, mm/min	V_s, m/min	$V_f$mm/min	S, mm/min	V_s, m/min	$V_f$mm/min	S, mm/min	V_s, m/min
935	3	120	647	2,037	80	377	1,137	40
903	2,893	116	616	1,937	76	346	1,03	36
871	2,786	112	585	1,837	72	315	0,923	32

839	2,679	108	554	1,737	68	284	0,816	28
807	2,572	104	523	1,637	64	253	0,709	24
775	2,465	100	492	1,537	70	222	0,602	20
743	2,358	96	461	1,437	66	191	0,495	16
711	2,251	92	430	1,337	62	160	0,388	12
679	2,144	88	399	1,237	58	129	0,281	8
647	2,037	84	368	1,137	54	98	0,174	4

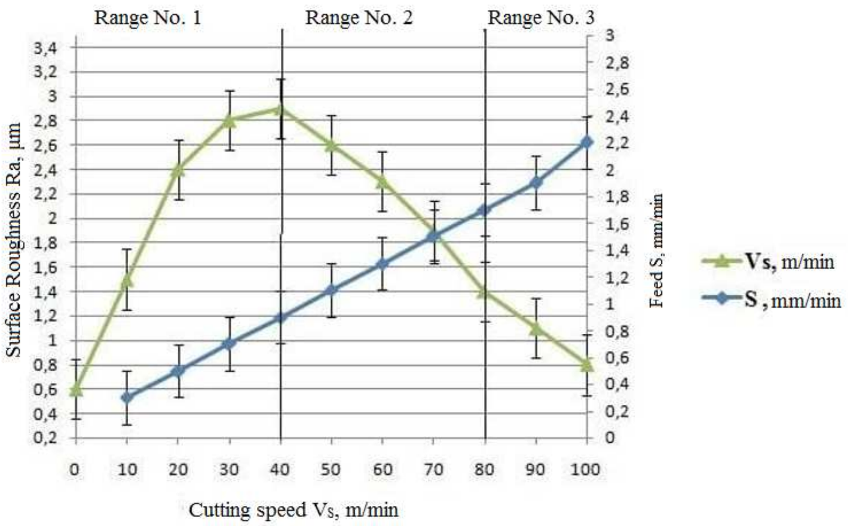


Figure 8: Graph of the influence of Cutting Conditions on the Surface Roughness, Ra.

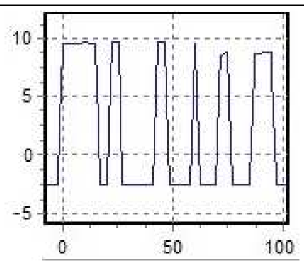
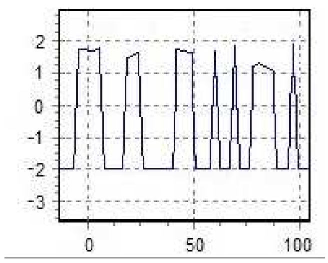
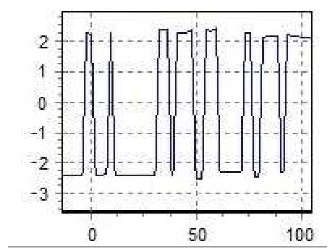
№	Range No. 1	Range No. 2	Range No. 3
RoughnessProfiler			
Ra	Ra=5.801	Ra=1.899	Ra=2.275

Figure 9: Roughness values Depending on Cutting Conditions

To confirm the hypothesis of the influence of optimal cutting conditions on the quality of the processed surface, a three-factor experiment is developed [23-25]. With regard to factors, the cutting modes are adopted: cutting speed V_s, feed S, and angular velocity per tooth V_f. The surface roughness Ra (μm) is adopted as optimization parameters, which have a significant effect on the quality of the implant surface [24]. To determine the coefficients of the processing parameters and construct the regression equations, the logarithm data are given (Table 3). When choosing the area of the experiment, the limiting values of the processing modes are used, which are set in the ranges No. 1,2,3.

Table 3: Logarithmic Data Processing Modes

№	S, mm/min	ln(S)	V_s, m/min	ln(V_s)	Ra, μm	ln(Ra)
1	3	1,099	120	4,787	3	1,099
2	2,7	0,993	108	4,682	2,76	1,015

3	2,4	0,875	96	4,564	2,52	0,924
4	2,1	0,742	84	4,431	2,28	0,824
5	1,8	0,588	72	4,277	2,04	0,713
6	1,5	0,405	60	4,094	1,8	0,588
7	1,2	0,182	48	3,871	1,56	0,445
8	0,9	-0,105	36	3,584	1,32	0,278
9	0,6	-0,511	24	3,178	1,08	0,077
10	0,3	-1,204	12	2,485	0,84	-0,174

Using the logarithm in the Deductor Studio Academic program, the regression equations coefficients and the factors degree value are found (Table 4).

Table 4: The Parameters value of the Constant Coefficient and Factors Degree

Factors	Parameters	Degreedesignation	Value	Ra, µm
C	Coefficient	C	0,00086	1,6
S	Feed	a	-2,461	
Vs	Cuttingspeed	b	3,647	

The logarithmic dependence of surface roughness on a constant coefficient C and active factors is expressed by the following regression equation (1):

$$\ln(Ra) = C \cdot \ln[S]^{a} \cdot \ln[Vs]^{b} \quad (1)$$

The regression equation for the dependence of roughness on variable factors, a constant coefficient and transformed into power for each of the optimization parameters take the final dependence (2):

$$Ra = 0.00086 \cdot \ln[S]^{-2.461} \cdot \ln[Vs]^{3.647} \quad (2)$$

Using the derived regression formula, the optimal parameters of the cutting conditions are substituted and obtained [26-29]:

$Ra = 0{,}00086 \cdot 0{,}405^{-2.461} \cdot 4{,}277^{3.647} = 1{,}6$µmThus, the optimization method was applied to achieve a balance between improved surface quality and maintaining an acceptable material removal rate [30-36].

CONCLUSIONS

- The microstructure and double phase transition diagram of the titanium-aluminum alloy indicates that in the crystalline state, Grade 5 consists of a fine-grained α phase with a body-centered cubic lattice.
- The use of cutting fluids STRUB StabilioCut coolant and the calculated optimal cutting conditions can reduce the temperature from the tool contact zone of 1100-1200ºC, below the polymorphic transformation from 822ºC for pure titanium.
- It has been established that the main parameters affecting the surface roughness Ra are the cutting speed VS, m/min; feed S, mm/min. The angular velocity per cutter tooth Vf is proportional to the angular velocity and this parameter can be neglected.
- The optimal modes of implant processing were experimentally determined: cutting speed VS = 70 m/min and feed S = 1.5 mm/min, while the roughness value Ra = 1.8 µm. The selected parameters provide a combination of improved surface quality at an acceptable cutting speed of the material.

- Based on the results of a multivariate experiment, regression equations were obtained, which is expressed by the dependence: Ra = 0.00086·S-2.461·Vs3.647.

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